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Mobile WiMAX: Multi-Cell Network Evaluation and Capacity Optimization

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Abstract—The performance of a mobile WiMAX system is highly dependent on the application environment. Local clutter has a significant impact on the path loss exponent and the observed multipath statistics. The spectral efficiency of a WiMAX network can be enhanced if channel quality information is included as part of the system optimization process. This paper presents a comprehensive study of such a scenario, with numerical analysis of mobile WiMAX presented for a multi-cell deployment. In order to achieve high coverage and throughput to a large number of users, handover (HO) and link adaptation (LA) strategies are addressed. Interference is spatially separated through the use of dynamic channel allocation and WiMAX user assignment. Results show that coverage to 98% of the service area is achieved with an average throughput of 3.88 Mbps per sector. This is based on a 5MHz (512-FFT) OFDMA TDD profile (using one-third fractional reuse) deployed in licensed 3.5 GHz spectrum.

Keywords- WiMAX, OFDMA, Interference, Handover, Link adaptation, channel allocation

I. INTRODUCTION

WiMAX (worldwide interoperability for microwave access) represents an IEEE metropolitan access standard (IEEE 16d/e/j/m) that provides broadband wireless IP (internet protocol) to fixed CPEs (customer premises equipment) and mobile terminals. The system offers a wide variety of services, including voice, data and multimedia. The full potential of the WiMAX standard will be realized as the recent nomadic and mobile extensions are deployed. Given the finalization of the IEEE 802.16e standard [1], and the upcoming test and certification of WiMAX products [2][3], mobile broadband services are about to become a reality. WiMAX operation is currently active in a number of licensed bands at 2-4 GHz. Unlicensed operation (at significantly lower transmit powers) is also permitted at the top end of the 5 GHz band. In the licensed case, reliable non-line-of-sight (NLoS) operation can be achieved to mobile users over a number of kilometers. Within the standard, multiple FFT sizes are specified {128, 512, 1024 and 2048} and this facilitates scalable channel bandwidths from 1.25 MHz to 20 MHz. The performance of mobile WiMAX (based on the published standard) has been widely evaluated in [2][4]-[7].

It is well known that cellular system performance is fundamentally limited by signal interference from concurrent co-channel and adjacent channel transmissions. The combination of long transmission range (e.g. macro-cells) and high data capacity (multi-mega bit per second aggregate throughputs) is a significant challenge. A scheduler is required to manage radio resource allocation. This algorithm must minimize interference on the uplink and downlink. Furthermore, it must ensure a fair and efficient distribution of the available resources. The 802.16e standard supports a number of advanced physical layer techniques, such as adaptive modulation and

coding (AMC), multiple-input multiple-output (MIMO) transmission modes, and scalable orthogonal frequency division multiple access (SOFDMA). These can be used intelligently to enhance diversity gain and multi-user performance [4][7]. There are a number of ways to take advantage of multi-user diversity, AMC and flexible resource allocation. These are not specified in the IEEE standard and are a key differentiator between vendor solutions. 802.16e supports mobility management to enable the seamless handover (HO) of ongoing mobile connections from one base station (BS) to another. Three HO methods are defined. Hard handover (HHO) is mandatory, while fast base station switching (FBSS) and macro diversity handover (MDHO) are left as superior options.

The radio channel plays a key role in the evaluation of transceiver parameters (such as link adaptation (LA), HO and multi-user scheduling). The underlying scenario for mobile WiMAX is an outdoor environment with large numbers of multiple users. In an urban environment, the surrounding buildings normally result in deep radio shadows and severe multipath. In addition, interference can further degrade the signal quality. When deploying WiMAX in a multi-cell network, it is important to take the propagation channel and the potential for interference into account. In this paper, a site specific ray-tracing propagation model is used to provide realistic urban channel data. This is based on a downtown section of Bristol (UK). We use the estimated signal to interference plus noise ratio (SINR) and the link throughput to drive the processes of HO and WiMAX user assignment. Furthermore, by applying dynamic channel allocation, both the intra-cell and inter-cell interference are spatially separated. As a result, excellent coverage and throughput results are achieved within our test scenario. The study is based on the use of licensed 3.5 GHz spectrum. The 5 MHz (512-FFT) OFDMA TDD profile is used throughout [1][3][7].

The rest of the paper is organized as follows: Section II analyses the impact of interference in a multi-cell WiMAX network. Section III describes the system optimization procedure, including that of HO, LA and user assignment. In section IV, a range of simulation results are presented for a mobile WiMAX network with users spread across a number of cells. Finally, conclusions are presented in section V.

II. INTERFERENCE IN A MOBILE WiMAX NETWORK

Fig.1 illustrates a multi-cell WiMAX network deployment based on the 512-FFT DL PUSC (partial usage of sub-channels) OFDMA TDD profile. A total of 15 sub-channels (30 clusters) are mapped to one OFDMA symbol. Since the subchannel is the smallest allocation unit for a user on the DL, this profile can support up to 15 users per slot. In order to avoid intra-cell interference within a cell, three sectors are employed at each BS and a frequency reuse factor of one (resource being fractionally

split between the sectors) is applied. Each sector has access to one-third of the total number of clusters. Ideally, there would be no interference between users in a cell. However, if users from neighbouring cells are transmitting on the same subcarrier and time slot, then co-channel interference (CCI) can occur. Fig.1 shows how downlink interference can occur in an OFDMA system. This can result in serious system level degradation. A multi-cell network must therefore perform some degree of interference management (normally based on interference avoidance and/or cancellation).

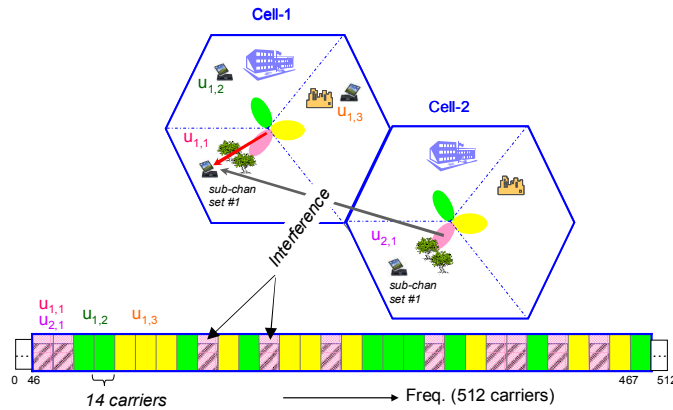


Figure 1. Co-channel interference in an OFDMA system (downlink).

If we assume that a total of K users are deployed within the multi-cell WiMAX network, and only a subset of the N_k subcarriers are assigned to the k -th user, then the downlink interference can be quantified using the equation below

$$I_k = \sum_{i=1}^{N_k} \sum_{\substack{u=1 \\ u \neq k}}^K \rho_{u,l_i} P_{u,l_i} |h_{u,l_i}|^2 \quad (1)$$

where P_{u,l_i} and h_{u,l_i} denote the average received power (across the channel bandwidth) and the fast fading observed on the l_i -th subcarrier of the u -th user. ρ_{u,l_i} takes a value of one or zero to indicate whether subcarrier l_i is assigned to the accessed user. $R_k = [l_1, l_2, \dots, l_{N_k}]$ is used to define the subcarrier allocation for the k -th user. Hence, the SINR for the k -th user can be expressed as

$$SINR_k = \frac{\sum_{l=1}^{N_k} P_{k,l} |h_{k,l}|^2}{\sum_{i=1}^{N_k} \sum_{\substack{u=1 \\ u \neq k}}^K \rho_{u,l_i} P_{u,l_i} |h_{u,l_i}|^2 + \sigma^2 B} \quad (2)$$

where σ^2 and B represent the noise variance and the channel bandwidth respectively. The theoretical system throughput for a SISO system (single-input single output) can be derived from the well-known Shannon capacity using the expression below

$$C_{total} = \sum_{u=1}^K \log_2(1 + SINR_k) \quad \text{bps / Hz} \quad (3)$$

Clearly, the throughput is determined by the quality of the channel, the level of interference, and the choice of subcarrier sets allocated to each user. From our link level simulations, the throughput (in bps) for the k -th link is obtained using packet error (PER) and AMC by the following expression

$$C_k = \frac{N_k N_b \gamma_k}{T_s} \times (1 - PER_k) \quad (4)$$

where T_s , N_b and γ_k denote the OFDMA symbol duration, the number of bits per subcarrier and the FEC coding rate for the k -th user. A high link throughput can be obtained by employing a higher AMC mode or by increasing the number of assigned sub-channels. However, higher AMC modes cannot be supported in the case of low SINR. Also, there is a trade-off between multi-user diversity and frequency diversity, and N_k should be selected carefully based on the quality of the channels. This implies that a combination of AMC and flexible sub-channelization is required to maximize the link performance.

III. HO, LA AND USER ASSIGNMENT STRATEGY

For a multi-cell mobile WiMAX network, system optimization can be used to enhance aggregate throughput and coverage while maintain low latency. The principles of OFDMA allow a number of different users to share the FFT space. To take advantage of multi-user diversity and AMC, the scheduler needs to determine which subset of users can transmit in any given slot, and how best to allocate their subcarriers and power levels. This paper focuses on terminal mobility, subchannel allocation, and ideal HO with fairness amongst all the users in the network. In order to optimize the system and ensure overall QoS, we use the minimum receiver sensitivity values (as specified in 802.16e) to determine whether or not it is viable to transmit data to the user. If transmission is possible then the SINR estimate is used to select the highest possible link-speed. The HHO process is based on determining the BS that offers the highest link-speed. We do not base the HHO decision entirely on SINR since this value can change abruptly between cells and/or sectors.

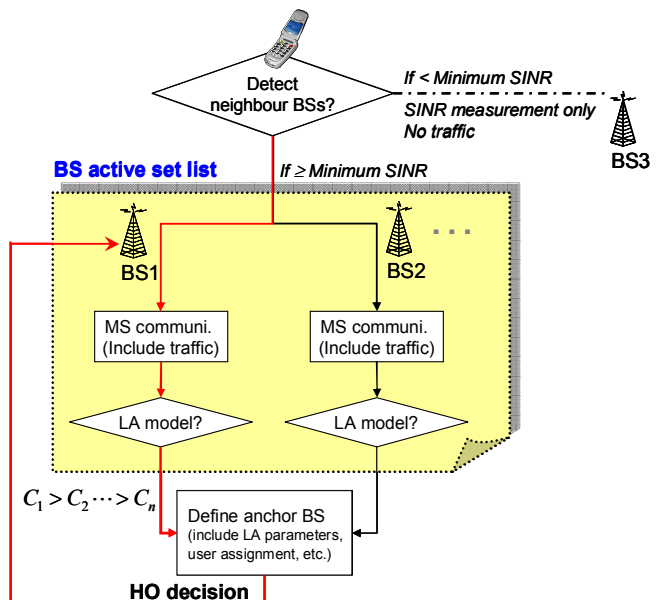


Figure 2. Cell selection on a per-slot basis

The received SINR from any neighboring BS is calculated at the MS on a per-slot basis. Once the MS has satisfied the SINR (for the lowest $\frac{1}{2}$ rate QPSK link-speed), it will maintain a valid connection with one or more BSs simultaneously, and must be synchronized with the basestation's DL transmission slots. If the received SINR is too low, the connection is terminated. During scanning intervals (which are allocated by the MAC management message), the MS attempts to achieve maximal throughput via LA. Each MS reports its HO decision on the CQICH (channel quality information channel) based on measured results, as depicted in Fig.2. The MSs are also allowed to optionally performing ranging (to synchronize the symbol and equalize the received power levels among various MSs) for each sector transmission. Each user is sent data via an assigned sector of a certain BS. A set of subcarriers are then defined according to the subchannel allocation. These are determined by the measured SINRs across the subcarrier sets. It should be noted that the set of subcarriers is spread out over the entire bandwidth after renumbering and permuting (which leads to an increased frequency diversity gain) as shown in Fig.1. Given effective cell selection and channel allocation, both the intra-cell interference and the inter-cell interference are spatially controlled within and between cells.

The BS active set needs to be continuously monitored. As the MS move several system level parameters, such as the subchannel allocation, the choice of link-speed, the choice of transmit sector, and the BS active set, should be dynamically updated. This ensures that maximal throughput and high QoS is maintained over the entire region.

IV. NUMERICAL RESULTS

A. Simulated system profile and link performance

For case of 512-FFT DL PUSC OFDMA operating in a 5MHz channel bandwidth, a total of 15 sub-channels are mapped to one OFDMA symbol. There are 3 groups (one per sector), with 5 subchannels in each group, and each sub-channel comprises 24 data subcarriers and 4 pilot subcarriers. In this paper we use a three sector BS to transmit on the DL to three users (one in each sector) in each OFDMA symbol, thus 120 subcarriers are assigned to each user. The link-level simulation parameters are listed in Table 1 and Table 2.

TABLE I. LINK SIMULATOR PARAMETERS

Parameters	Values
Bandwidth	5 MHz
FFT size	512
Useful symbol time	89.6 μ s
Guard time	11.2 μ s
Cyclic Prefix	1/8
Subcarrier spacing	11.16071429 kHz
FEC coding	Convolution code
No. of simulated FEC code block	1000

Since the MS can be held at arbitrary orientation, and also since some devices (such as laptops) may use directive antennas, the channel gain is difficult to predict (here we assume a random orientation). Given the assumption of ideal channel estimation, Fig. 3 presents the bit error rate (BER) and link capacity for a SISO system experiencing narrowband Rayleigh fading (i.e. a worst case NLoS channel). Results show that an

approximate SNR of 7 dB is required for the lowest link-speed ($\frac{1}{2}$ rate QPSK). More than 30 dB is required for the $\frac{3}{4}$ rate 64QAM mode to achieve the maximum DL peak throughput of 5.36 Mbps/sector.

TABLE II. FEC BLOCK SIZE

Model	Coded bits per sub-carrier	Coded bits per OFDMA symbol	Nominal bits rate (Mbps)
1/2 QPSK	2	240	1.19
3/4 QPSK	2	240	1.79
1/2 16QAM	4	380	2.38
3/4 16QAM	4	380	3.57
2/3 64QAM	6	720	4.76
3/4 64QAM	6	720	5.36

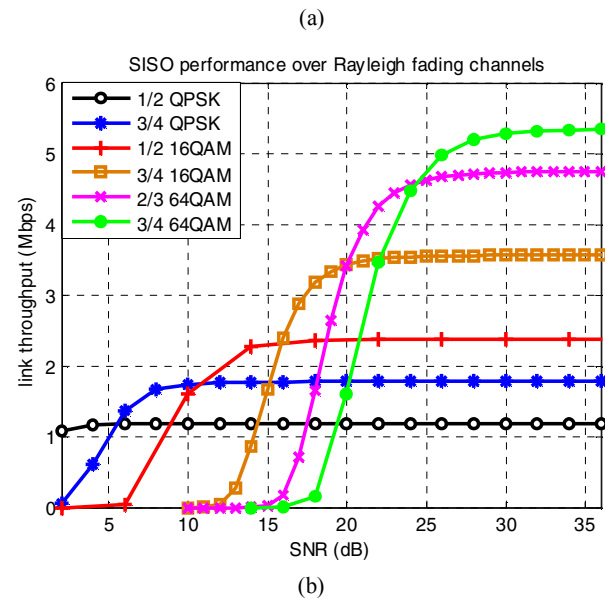
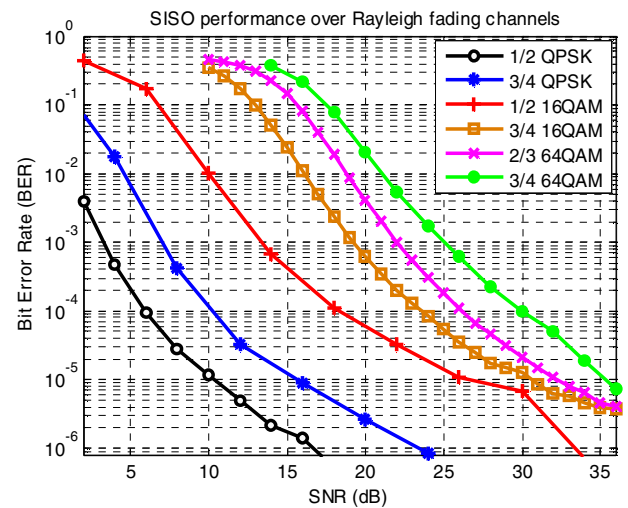
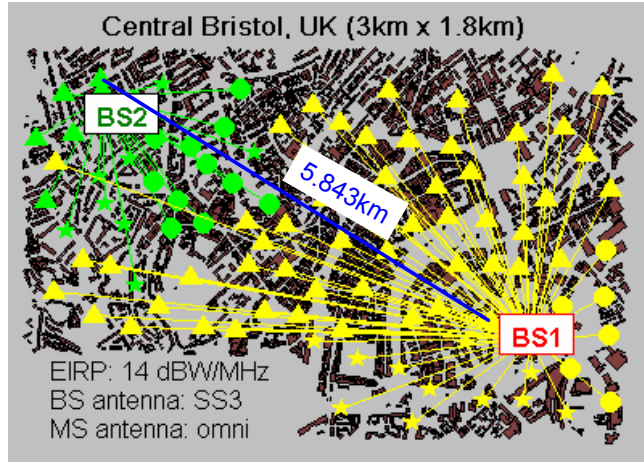


Figure 3. Link-level performance under Rayleigh channel (3 user OFDMA)

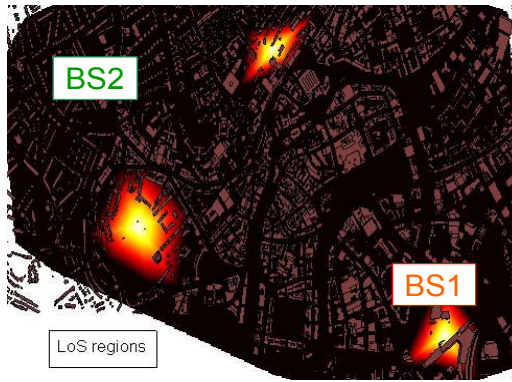
B. System performance

This section presents a set of results for the LA and HO optimization described in section III. Within the study, all users

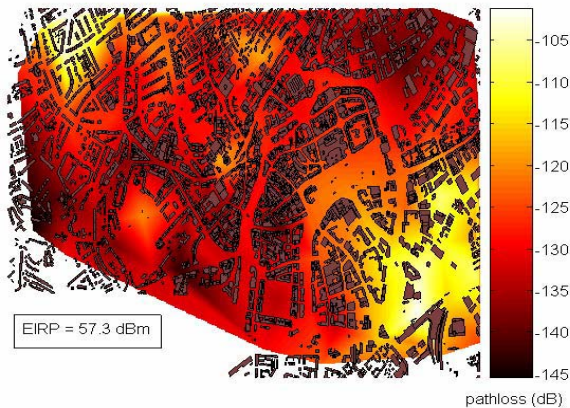
have an equal opportunity to access the BS (i.e. the scheduler is fair). As discussed before, downlink interference and its impact on system performance is highly dependent on the application environment. This cannot easily be represented using a statistical channel model. Instead, a ray-tracing tool is used to model the propagation as the mobile terminal move across environmental transition regions (i.e. from an urban street canyon to more open park land). The ray-tracing model is able to trace electromagnetic waves in 3-D space, and includes the influence of specific buildings, terrain and foliage. The model has been verified against measurement data in [8], and has been used in numerous prior WLAN and WiMAX system studies [5][9][10].



(a)



(b)



(c)

Figure 4. Simulation scenario. (a) MS-sector-BS assignment (b) LoS regions (c) Path-loss

A mobile WiMAX network scenario is considered that covers downtown Bristol. The main centre covers a 3km x 1.8km area. This is served by two BS (see Fig.4(a)), which are located on tall buildings (both 30m above ground level). A total of 100 MS are distributed at ground level (at a height of 1.5m AGL). Firstly, the spatial channel impulse response (CIR) is traced between all MS and BS. This is performed using isotropic antenna patterns at the BS and MS. This provides information on the amplitude, phase, time-delay, angle-of-arrival (AoA) and angle-of-departure (AoD) for each of the multi-path components (MPC). Single-beam sectorised (SS) and omni-directional antennas (with 0 dBi gain) are employed at the BSs and MSs respectively [11]. We further assume a sector antenna gain of 15 dBi to produce an effective isotropic radiated power (EIRP) of 57.3 dBm (which is compliant with the latest OFCOM regulations for licensed WiMAX systems in the UK). Each MS then measures the downlink SINR from all neighboring BSs. A system noise figure of 8 dB and an implementation margin of 5 dB are also used in the link budgets. Fig.4(b) indicates that NLoS dominates in the operating environment, with only a handful of regions enjoying LoS. Fig.4(c) shows the predicted path-loss (to the most likely BS) in this urban region.

The SINR is used to determine which BS and which sector should be used to serve each MS. This is defined as the BS/sector combination that offers the maximum SINR. Next, appropriate sub-channels are assigned to each user; this is

performed by selecting the best subset of $\sum_{l=1}^{N_k} |h_{k,l}|^2$ for the three users. Fig.5 presents the SINR distribution after the cell and sector selection process.

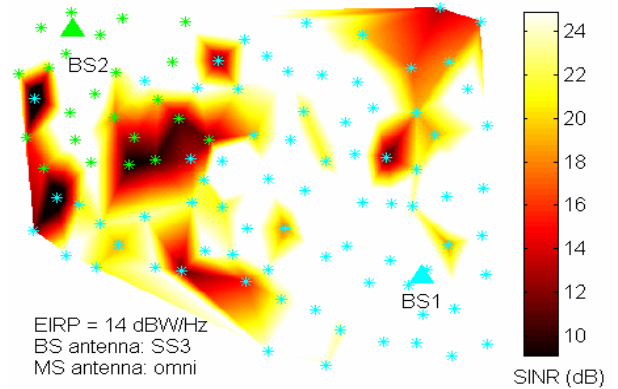


Figure 5. SINR measurement

Users assigned to different segments at the same time perform OFDMA symbol mapping. Channel data for those assigned users also feeds into the PHY simulator. We assume that the DL frame preamble provides the MSs with the necessary time and frequency synchronization. The optimal modulation, coding rate and FEC block size are determined by the SINR and the projected PER, as described in section III. For the LA, we choose the AMC link-speed that maximizes the throughput, while maintaining a *PER* < 10%.

Fig.6 illustrates the HO region (as a grey zone) and the LA boundaries. Normally we would expect the lowest throughputs to mobile in the HO region. This occurs since they are likely to experience the highest levels of path-loss and interference (see Fig.4 (c) and Fig.5). Fig.6 also shows how the link throughput varies for a single MS as it moves only a route between the two BS.

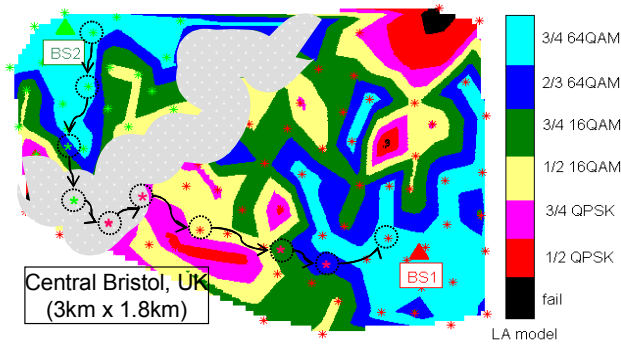


Figure 6. HO region and LA boundaries

It can be seen that the LA model performs differently under different link conditions. The throughput tends to drop as the MS moves away from BSs. At the cell edges the link throughput drops to 2.38 Mbps/sector (using the $\frac{1}{2}$ rate 16QAM mode). The highest link-speed ($\frac{3}{4}$ rate 64QAM) is mainly used at locations close to the BSs (and this gives a 5.36 Mbps/sector throughput). The calculated average throughput does not include the overhead of the MAP, which is outside the scope of this paper. For the coverage area, only 2% of locations lies in outage, and 49% of users are able to achieve the highest 5.36 Mbps throughput, as shown in Fig.7. The system achieves an average throughput of 3.88 Mbps/sector.

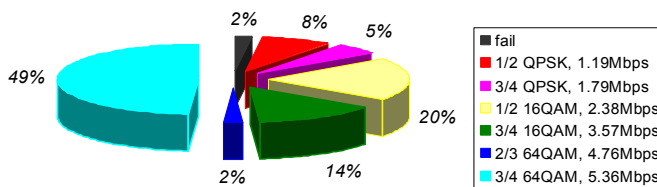


Figure 7. System throughput and coverage

CONCLUSIONS

The performance of a mobile WiMAX system is highly dependent on the PHY configuration, the protocol definition, the antenna types (BS beam pattern and array geometry), the operational environment, and the algorithms used in the scheduler. Achieving a high throughput and a low outage level can be challenging. The goal of this paper was to evaluate the performance of a multi-cell mobile WiMAX system. In particular, the work focused on the expected downlink performance and the management of interference in these links. The use of LA and HO was also studied.

In principle, a WiMAX system must be designed to avoid interference through a combination of network planning and

effective radio resource management. To ensure overall QoS and to optimize the system performance, effective handover decisions must be made to main the best link throughput and SINR. Dynamic subchannel allocation can be used to enhance the multi-user performance.

When the benefits of interference management, AMC and flexible multiuser assignment are combined, strong network coverage and average throughput can be achieved. For a realistic urban application, an average data rate of 3.88 Mbps per sector was achieved using a single 5 MHz channel (assuming fractional reuse between the three sectors).

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